Introduction to the Plasma Issue*

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Guest Editors

THE study of the physics of ionized gases has had a long and complicated history. The word "plasma" was first coined by Langmuir and Tonks in 1929 to denote a gas in which an important fraction of the molecules are dissociated into ions and electrons, the gas as a whole remaining electrically neutral. The laboratory study of plasmas, of course, had been pursued long before that, many important discoveries in the realm of gas discharge phenomena having been made in the 1800's. These studies, continuing into the Twentieth Century as exemplified by the work of Langmuir, served as the foundation for many practical electronic devices used for the generation, rectification, and control of electrical energy. The plasmas used in these devices usually have a low-charge density, and the fractional ionization is ordinarily less than one per cent. This small percentage of ionization is sufficient to provide good electrical conductivity which can be controlled externally, but it is difficult to study theoretically because of the numerous competing processes involving neutral atoms, metastable atoms, ions, electrons, and collective oscillations of ions and electrons.

With the progress made in astronomy and theoretical physics in the early part of the Twentieth Century, it was realized that most of the matter in the Universe, that in the stars, exists in the fully ionized state. Thus, a new form of plasma physics evolved in which the study was largely theoretical, and was concerned with matter at immensely high temperatures and pressures, the latter being balanced by the gravitational forces of the stars. Much of the work currently of interest and many of the men of greatest stature in the field of plasma physics started in the field of astrophysics.

Recently the astrophysicists have tackled problems which are more earthbound, although hardly any less exotic. The advent of an understanding of thermonuclear fusion, and its possibilities for the generation of power, have created a great deal of activity concerned with high density, high temperature plasmas of terrestrial design. Since these cannot be confined by gravitational forces as they are in the stars, magnetic methods of confinement must be used, and a large amount of theoretical and experimental work has been conducted with an eye toward the generation and containment of hot dense plasmas by magnetic fields. In the U.S.A., this area of study began under the AEC-sponsored Sherwood project, which was originally highly classified, and thus developed a language and fraternity of its own before most of it was declassified in 1958.

A third group of investigators in the realm of plasma physics consists of those who were originally aerodynamicists. As airborne vehicles move faster and faster, their effect on the environment increases. One of the principle manifestations of this is the increasing temperature, eventually reaching a range in which appreciable ionization takes place, making the air conductive. The equations of gas dynamics are modified by this conductivity, and thus plasma physics is an important area of study for those in the missile and aircraft fields. In addition, the high temperatures which exist in rocket flames lead to appreciable ionization, and the conductivity of this material may be an important consideration. Recently, the desirability of extremely high velocity rocket exhaust has led to attempts to use electrically-accelerated particles for rocket propulsion.

Finally, we should discuss the field of radio propagation which has made important contributions to the understanding of plasmas and their interaction with electromagnetic radiation. It has long been recognized that portions of the earth's upper atmosphere are ionized enough to cause refraction and reflection of radio waves. The basis for much of the world's long range communication is the fact that the ionospheric layers will reflect radio signals with greater or lesser amounts of attenuation depending on the frequency, ion (and thus electron) density, and altitude (and thus the neutral density). In order to understand and make use of this phenomenon, many contributions had to be made to the understanding of the behavior of the ionosphere and the influence of a plasma on radio signals. Closely related to this has been a study of more recent origin which arises because of the high-speed aircraft and missile phenomena which concern the aerodynamicists. In spite of the plasma sheath surrounding these vehicles, we must communicate with them, and some interesting problems have been attacked, and system proposals have been evolved. The properties of this plasma sheath also result in some interesting radar return properties, with obvious military interest. (It should be noted that the word "sheath" in this context means the layer of plasma surrounding a a vehicle; much earlier, the word was used by Langmuir, and still is used by gas discharge physicists and engineers to denote the non-neutral layer which surrounds the plasma in a discharge. The reader should beware of this ambiguity.)

Plasma physics, then, might be divided up into four major disciplines, separated not so much by the concepts

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used as by their historical aims and the interests of those involved. These might be denoted by the following names: gas discharges, fusion plasma physics (including astrophysical applications), aerodynamical applications, and radio propagation plasma studies. As might be expected, this special issue of the PROCEEDINGS is aimed predominantly at the electronics engineer and emphasizes the fields most concerned with the communication and electronics arts, namely gas discharges and radio propagation. It has been our intention in laying out this issue to make it largely one in which the basic principles and known fundamentals of plasma physics are expounded as they apply to problems in these areas, without concentrating on specific devices and techniques. Wherever possible, the fundamentals are emphasized and detailed engineering concepts omitted. It is our hope that in this way an issue of reasonable size will communicate many of the basic ideas, and stimulate the reader's interest in some of the areas of plasma physics and its engineering applications.

With this background, let us scan this special issue on plasma physics.

Plasma Physics—An Elementary Review, (*Bachynski, p. 1751*). This paper summarizes most of the areas of current interest in plasma physics, and serves as a background article for almost all of the rest of the issue. The thermonuclear problem, astrophysics, propagation, noise, propulsion, and electronic devices are all treated in a form which allows the reader to grasp the basic concepts preparatory to reading the specialized articles.

Oscillations and Noise in Low-Pressure DC Discharges, (*Crawford and Kino, p. 1767*). All laboratory discharges seem to be plagued with an excess amount of low frequency noise. and in special cases, oscillation. In this paper the authors review the history of scientific investigation into this phenomenon, and present in a coherent package the bulk of present day knowledge about this noise as well as some tantalizing suggestions for controlling it. These phenomena take place in two different frequency ranges, the first generally below one megacycle and dominated in some manner by the ionic properties, and the second in the microwave range typically governed by the electron plasma frequency. The complete explanation of the source of either of these forms of noise is still lacking. However, much experimental data exists, and a qualitative picture has been presented which is consistent with the observations.

Ionic and Plasma Propulsion for Space Vehicles, (*Brewer, Currie, and Knechtli, p. 1789*). In their search for higher specific impulse (thrust per unit mass of propellant), rocket experts have turned to electrical acceleration of ions or plasmas as a potentially practical method for obtaining this objective. The engineering techniques required are an interesting mixture of electronics, power conversion, and astronautics. The authors of this paper present an outline of the basic principles underlying this line of approach, and follow with the basic system concepts appropriate to two somewhat different techniques, the ion engine in which ions are accelerated and then mixed with electrons to form a plasma, and the plasma rocket in which the neutral combination of ions and electrons is accelerated. A number of specific techniques are illustrated and the basic technological problems are presented. In this area, as with many space instrumentation problems, high efficiency, high-power electrical sources will be necessary for practical utilization of these techniques.

Transmission of Electromagnetic Waves Through an Ionized Layer in the Presence of a Strong Magnetic Field, (*Harley and Tyras, p. 1822*). This paper attacks the same problem, that is, the enhancement of propagation through a plasma by the use of a magnetic field. The plasma is approximated here by a succession of slabs so that the variations in density may be reasonably represented. A numerical calculation is given showing the transmission as a function of magnetic field for a specific model of density variation.

The Use of Magnetic Fields in the Elimination of the Re-Entry Radio Blackout, (*Hodara, p. 1825*). The effect of a plasma sheath on a re-entering space vehicle is to greatly reduce the high frequency propagation through this sheath. This paper discusses the technique of improving the communication with a space vehicle by imposing a magnetic field near the antenna which reduces the attenuation through the sheath.

RF Reflectance of Plasma Sheaths, (*Taylor, p. 1831*). As noted earlier, the plasma sheath about a re-entering space vehicle not only degrades the communication with it, but also changes markedly the radar return. This paper exhibits a calculation of the reflectance of a plane sheath which can be used as an approximation of the true sheath problem. The result is obtained in analytic form, in general as the ratio of two complex infinite series.

Mutual Coupling of Two Thin Infinitely-Long Slots Located on a Perfectly Conducting Plane in the Presence of a Uniform Plasma Layer, (*Yee, p. 1837*). The plasma sheath about a re-entering body is again considered, this time from a near-field point of view, in which the author considers the mutual coupling between two antennas located on the surface of the body. The result is expressed as a coupling coefficient between the two antennas. It is shown that the coupling is generally less than that which would exist in the absence of the plasma, provided the operating frequency is above the plasma frequency.

Antenna Noise Temperature in Plasma Environment, (*Bachynski, French, and Cloutier, p. 1846*). Again the reentry sheath is considered. In this paper, the authors are concerned with the degree to which the plasma itself contributes noise energy to the antenna. Since the sheath is at an extremely high temperature, even a small degree of coupling to the plasma may result in badly degraded noise performance. The analysis shows a peak in noise temperature in the vicinity of the plasma frequency, above which the noise is principally external, and below which it arises mostly in the vehicle. Because auxiliary magnetic fields may also be used in these vehicles, the calculations have been extended to include the appropriate anisotropy. The noise then exhibits peaks at both plasma and cyclotron frequencies, but the structure is much more complicated, and general conclusions are harder to draw.

Generalized Appleton-Hartree Equation for any Degree of Ionization and Application to the Ionosphere, (*Shkarofsky, p. 1857*). This paper is motivated by the problems of ionospheric propagation, but may have much broader application. The author formulates the generalized equations for propagation of electromagnetic waves through a plasma, when the collisions result from both electron-neutral and electron-ion collisions in arbitrary mixtures. The analysis is compared with experimental results, and a proposal is made that ionospheric electron temperatures may be measured by correlating sufficient propagation data.

The Electrical Conductivity of a Partially Ionized Gas, (*Sengupta, p. 1872*). The problem of conductivity of a plasma is considered theoretically over the range where both electron-neutral, and electron ion collisions are important. Explicit expressions for both the real and imaginary parts of the conductivity are given in integral form. While these general forms are applicable to any degree of ionization, the author also presents expressions for the same quantities for the case that the plasma is fully ionized, in which case the conductivity may be expressed in terms of known transcendental functions.

Interaction of Microwaves in Gaseous Plasmas Immersed in Magnetic Fields, (*Rao, Verdeyen and Goldstein, p. 1887*). The 1930's saw the discovery of the Luxembourg effect, in which a strong radio transmitter passed its own modulating intelligence onto other signals whose propagation path passed over the region of the transmitter. Correctly explained as a nonlinear plasma effect (cross-modulation) in the ionosphere, the phenomenon has its modern counterpart and extension scaled down to laboratory size by use of microwaves. This paper covers basic studies of plasma characteristics in a strong 5 Gc/sec microwave field, using a weak sensing signal at 6 Gc/sec for the measurements. A magnetic field swept through cyclotron resonance is also used. The data are all taken in the inherently equilibrium state of the afterglow, using pulse techniques; thus, the rise in electron temperature due to absorption of power, and the changes in collision frequency, can be used for analytic comparison of the data with theory. Good qualitative agreement is found.

Frequency Conversion in a Microwave Plasma, (*Baird and Coleman, p. 1890*). Closely related to the above paper, is the present one in which plasma nonlinearity is used in a practical way to get microwave frequency multiplication and frequency mixing. The work indicates that the principal source of nonlinearity is modulation of the electron density at twice the drive frequency. Little or no magnetic field was used. In the experiments, a 9 Gc/sec high-level signal and 11 Gc/sec low-level signal produced a 20 Gc/sec output, about 25 to 30 db down; the same large conversion loss occurred for second harmonic generation. The values agree with those expected from this theory. Thus, the results are still rather far from useful, but it is expected that much higher power densities might improve matters.

A Plasma Microwave Detector, (*Taylor and Herskovitz, p. 1901*). In this paper, the authors describe a novel use of an activated plasma as a microwave detector. This is done in a most unusual way, by detecting the change in recombination radiation, as observed by a photomultiplier. It appears that the presence of microwaves changes the electron temperature slightly so as to reduce the recombination and to quench the light. Greatest sensitivity requires the low electron temperature of the afterglow equilibrium state. As little as a microwatt of input could be detected, which is rather remarkable even though it is considerably poorer than a video crystal. The authors point out that such a plasma detector is burn-out proof and has an extremely wide bandwidth. Several suggestions are proposed which might increase the sensitivity (with a reduction in bandwidth) but they have not yet been tried.

Interaction of a Modulated Electron Beam with a Plasma, (*Boyd, Gould, and Field, p. 1906*). There has been great interest in recent years in the use of electron-beams interacting with a gaseous plasma to produce microwave amplification. This paper describes the first successful experiments of a few years ago, in which the microwave modulation of an electron beam was increased by interaction with a "resonant" plasma. Later, traveling-wave amplification was achieved, by interaction with a slow propagating wave on the plasma column. These two different modes are compared and both theory and experiment are described. In the experiments, both helix coupling at 3 Gc/sec, and cavity coupling at 0.5 Gc/sec are employed. The observed gains of 7 db/cm in the plasma resonance case, though only half of the theoretical, are nevertheless significantly high. In the slow-wave case, about 0.8 db/cm is observed again well below theory. The discrepancies with theory are not unexpected because the theory assumes a uniform, loss-free plasma. Unfortunately, the present interactions are very noisy compared with conventional traveling-wave high-vacuum tubes.

A Method of Measurement of Flame Attenuation at 200 Mc, (*Biggs, p. 1917*). The first plasma ever produced by man on earth was the flame, *i.e.*, a gas ionized by its high temperature. Many years ago, the electrical conductivity of flame was studied, today it is once again of major importance in magnetohydrodynamic power generation or propulsion, and in missile trails. In the paper by Biggs, 200 Mc/sec measurements are described which can be used to obtain conductivity and dielectric constant of flames passing between a two-bar measuring line. Distilled water is used to calibrate, and theoretical curves are shown for electron densities ranging to 10^9 per cm^3.

Electrical Characteristics of a Penning Discharge, (Helmer and Jepsen, p. 1920). The Helmer and Jepsen paper concerns a most interesting type of magnetically-confined plasma known as the Penning discharge. Originally proposed as an ionization gauge, this discharge can take place at gas pressures as low as 10^{-12} mm of mercury, ordinarily considered an ultra-high vacuum. This type of discharge is the basis of the getter-ion vacuum pump. In this paper, it is shown that the trapping of electrons along the axis of symmetry is so effective that the axial potential is severely depressed. By a split anode structure, oscillations were obtained from the magnetron-like structure whose cathode is the space-charge cloud. With the normal anode, star-shaped sputtering patterns indicate that complex instabilities are present. Probably the most important result is the discovery that intense, nearly monochromatic, ion beams can be produced by such discharges.

Generation and Application of Highly Ionized Quiescent Cesium Plasma in Steady State, (Wada and Knechtli, p. 1926). This next paper covers work on the method of generating plasma which requires no electrical discharge. It has been known that highly ionized plasma can be generated by use of cesium vapor in the vicinity of a hot electron-emitting tantalum cathode. With two such plasma sources facing each other, and only a modest confining magnetic field, the authors show that plasma densities of 10^{12} per cm^3, and 90 per cent ionization, are obtained. This work is of importance in that such plasmas are basically quiescent, and need no applied electric field to maintain them. In practice, such plasmas are useful for physical measurements, in thermionic energy converters and in plasma sources for rocket propulsion.

A New Approach to Thermionic Energy Conversion, (Bernstein and Knechtli, p. 1932). The original work on high-efficiency thermionic energy converters used a self-generated cesium plasma resembling that described in the preceding paper. However, a low temperature electron emitter does not ordinarily release enough ionized cesium to make an efficient device. For a long time, workers have been trying to obtain an auxiliary source of ions which would not require too much energy to produce. In the Bernstein and Knechtli paper, such a source is described; while this work was going on, a similar concept was also explored independently in England. The structures devised appear to work well and to make a very important contribution to the low-temperature thermionic energy converter. In this paper, data on an argon plasma source are given; it is calculated that a 1500° K. cathode should be sufficient to provide an over-all efficiency of conversion of 25 per cent, if a sufficiently low work-function anode can be devised (*Editor's note:* a good low work-function anode is still a long way from realization). By modulating the plasma source, it should be possible to generate ac directly.

In concluding this Introduction, the *Editors* wish to thank the special group of reviewers who, although they must remain unnamed, are responsible for the selection of the papers, and much of the detailed editing of the papers.